

Semi-Annual Progress Report

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Task Objectives

The objectives of the last six months were:

- Evaluate the Version 2 algorithms for Fluorescence Line Height and Chlorophyll Fluorescence Efficiency
- Revise the Algorithm Theoretical Basis Document (ATBD) and participate in panel review
- Deploy bio-optical instrumentation at the Hawaii Ocean Time-series (HOT) site as part of the Joint Global Ocean Flux Study (JGOFS)
- Deploy bio-optical drifters in the Polar Front as part of JGOFS Antarctic Environment Southern Ocean Process study (AESOPS)
- Submit manuscript on bio-optical time scales as estimated from Lagrangian drifters
- Conduct chemostat experiments on fluorescence
- Continue development of advanced data system browser
- Continue to review plans for EOSDIS and assist ECS contractor.

Work Accomplished

Delivery of CFE and FLH Code

We are responsible for the delivery of two at-launch products for AM-1: Fluorescence line height (FLH) and chlorophyll fluorescence efficiency (CFE). In our last report we had planned to combine the two separate algorithms into a single piece of code. However, after discussions with Bob Evans (Univ. Miami), it was decided that it was best to leave the two algorithms separate. They have been integrated into the MOCEAN processing system, and given their low computational requirements, it is easier to keep them separate. In addition, there remain questions concerning the specific chlorophyll product that will be used for the CFE calculation. Presently, the CFE algorithm relies on the chlorophyll product produced by Ken Carder (Univ. South Florida). This product is based on a reflectance model, and is theoretically different than the chlorophyll product being provided by Dennis Clark (NOAA). These two products will be compared systematically in the coming months. If we decide to switch to the Clark product, then it will be simpler to modify the CFE algorithm if it remains separate from the FLH algorithm.

Our focus for the next six months is to refine the quality flags that were delivered as part of the algorithm last summer. A description of these flags was provided to Evans for the MOCEAN processing system. A summary was included in the revised ATBD. Some of the flags depend on flags produced by the input products (e.g., the Carder absorbed photons product, the Gordon water-leaving radiances, etc.) so coordination will be required.

ATBD Revision

A completely revised version of our Algorithm Theoretical Basis Document (ATBD) was delivered to the EOS Project Science Office in September. The revised ATBD contains a complete sensitivity study of the FLH algorithm which has just appeared in *Remote Sensing of the Environment* (Letelier, R.M., and M.R. Abbott, "An analysis of chlorophyll fluorescence algorithms for the Moderate Resolution Imaging

Spectrometer (MODIS)," Remote Sens. Environ., 58, 215-223, 1996). The ATBD also describes our approach to the estimation of the quantum yield of fluorescence which will form the basis of future physiologically-based productivity models.

We presented the revised ATBD and our response to the one external review at NASA Headquarters in early December. We were unable to attend the full review in November due to prior travel commitments. The only negative comment from the mail reviewer concerned our use of a straight baseline instead of a curved baseline for the FLH calculation. We noted that the uncertainties in the curved baseline approach were far larger than the straight baseline, and that we saw no particular value in introducing more uncertainty into the FLH process.

Algorithm Validation Activities

We are taking two approaches in our validation work for FLH and CFE. First, we are measuring sun-stimulated phytoplankton fluorescence in a wide variety of oceanographic conditions which will provide quantitative limits on the variability of FLH and CFE and the relationship of this variability to environmental and physiological factors. The most significant challenge in FLH and CFE will be its interpretation in the context of phytoplankton physiology. Second, we are quantifying the time and space scales of variability of fluorescence and productivity. These estimates will be used to develop quality assurance tests as well as to develop rigorous tests for product validation.

We are leveraging field opportunities to keep costs manageable. This past summer, we participated in a survey of the productive nearshore waters off the Olympic Peninsula in Washington. Surveys of chlorophyll, nutrients, productivity, and bio-optics were conducted within 10 km of the coast, a region of the ocean that is only occasionally sampled. The science focus was on the coupling between the shoreline ecosystem and the coastal ocean. We used a Tethered Spectroradiometer Buoy to collect water-leaving measurements close to the coast. These were compared with extracted chlorophyll from water samples. The relationship the bio-optical measurements and chlorophyll was quite good. We did not collect a sufficient number of samples to draw any conclusions on fluorescence, but we are proposing to NSF to make long time series measurements of optical properties in this region.

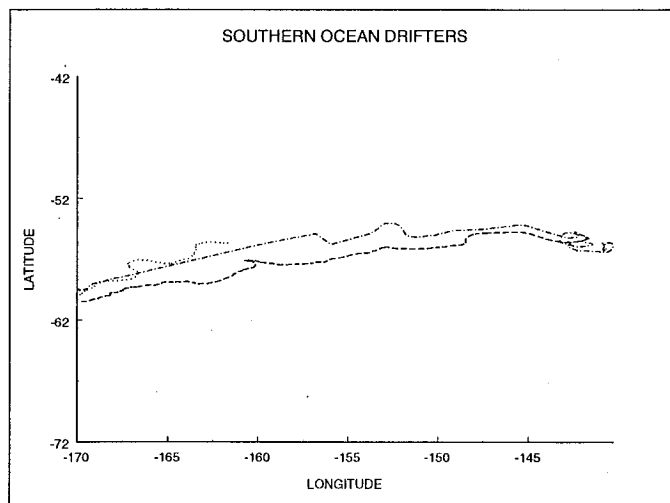
A longer term opportunity is presented by the U.S. JGOFS time series station in Hawaii (the Hawaii Ocean Time-series or HOT site). We have deployed a bio-optical sensor at the JGOFS Hawaii Ocean Time-Series station north of Oahu. The sensor package will be recovered in May 1997. We have also ordered the components necessary to assemble a second bio-optical sensor. This will allow us to service one unit and deploy the other unit. The HOT research team plans to maintain this mooring for the next several years. Given that it is visited monthly, this means we will have a full suite of biogeochemical observations to complement the bio-optical data. Last summer, we also participated in a cruise from HOT to the CLIMAX station, another long-term observing site in the central oligotrophic gyre of the Pacific. These data revealed the presence of a large subsurface phytoplankton bloom that had an optical signal characteristic of phycoerythrin-containing organisms. Initially, we thought that this bloom was composed of nitrogen-fixing cyanobacteria but microscopic analysis revealed that the bloom was composed mostly of diatoms. It appears likely that these diatoms have a symbiotic relationship with cyanobacteria which would result in the observed bio-optical signal.

Although such partnerships are an excellent way to improve scientific return and to reduce costs, one of the downsides is the inability to control schedules and activities. We had our bio-optical mooring equipment ready for deployment since the beginning of 1996, but we had to repeatedly delay because of ship scheduling and personnel issues that were out of our control. However, in the long run, such delays are minor compared with the eventual return.

Our second approach is to provide quantitative estimates of the scales of bio-optical variability, especially in the area of fluorescence. As reported earlier, there are significant differences onshore and offshore, reflecting changes in the scales of the physical environment. Two papers on these results are in press, and a third is in preparation. We have included one (a manuscript that will be published in SPIE Ocean Optics XIII) in the appendix.

Bio-optical drifters were deployed in the U.S. JGOFS program in the Southern Ocean known as AESOPS

(Antarctic Environment Southern Ocean Process Study). Part of AESOPS will focus on mesoscale variability in the Antarctic Polar Frontal Zone and its role in governing biogeochemical fluxes. The bio-optical and conventional drifters are equipped with GPS units to provide estimates of near-surface convergences and divergences associated with frontal meanders. These properties will be compared with an array of moored bio-optical sensors and high-resolution SeaSoar surveys of the biological and physical environment. These activities will largely be funded by the National Science Foundation, but MODIS funding has been used to acquire six bio-optical drifters to continue our algorithm validation activities at the high latitude Polar Front. Three of these drifters were deployed this September at the Polar Front. The drifter tracks are shown below. Note the strong meandering associated with the Polar Front. Unfortunately, one of the drifters failed early because of a defective battery pack, and another had high noise levels because of a bad wiring connection. METOCEAN Data Systems will provide a replacement drifter for deployment later this year. We are continuing to analyze the optical data from the drifters. The remaining three will be deployed this year in the main AESOPS field season. The FRR fluorometer will also be used during the next field season for assessments of the relationship between photosynthesis and fluorescence.



Algorithm Development

We have included a copy of a manuscript that is in press in *Geophysical Research Letters*. This paper documents the changes in FLH which can be used to estimate an apparent quantum yield of fluorescence. Variations in apparent quantum yield appear to be driven by changes in the nutrient regime, and this information could be used to improve models of primary productivity. Our approach is based on using this quantum yield to estimate P_{max} , which characterizes maximum photosynthesis in photosynthesis/irradiance experiments. P_{max} is critical variable in the present generation of productivity models.

We have acquired all of the necessary components to begin the long-delayed chemostat experiments. We will study the effects of nutrient and light history on the quantum yield of fluorescence. This work will provide a solid basis for the productivity algorithm.

At the Fall MODIS team meeting, Howard Gordon reported that the effects of scattering from whitecaps might be severe, especially in algorithms such as FLH, based on model studies. However, his recent work shows that this is unlikely to be a serious problem except for winds greater than 12 m/s. These results are based on field measurements in which the impact of whitecaps is small until the winds become strong and the sea surface is dominated by breaking waves. In such cases, it should be relatively straightforward to flag these pixels.

GLI Activities

The Japanese space agency, NASDA, released a Research Announcement soliciting proposals for algorithm development for GLI. This sensor is similar to MODIS and will launch in mid-1999 on ADEOS-II. MOCEAN will provide NASDA with copies of the MODIS oceans algorithms that we submit to the MODIS SDST. We will compare the equivalent MODIS data products with those from GLI. We expect to receive copies of the GLI algorithms as well. We will also pursue techniques to blend these two data products together and participate in joint validation and calibration activities to support data synthesis. Our plan has evolved to include the hiring of a full-time person at OSU to act as the "point person" for MODIS/GLI integration for the oceans data products. A search is presently underway for someone to take this position. We have several applicants, some of whom are outstanding.

EOSDIS Plans

We are continuing our work with Web browser interfaces to our data base of in situ bio-optical measurements and satellite imagery. We presently have 60 GB of data in our archive, and we are prepared to handle OCTS and SeaWiFS imagery when it becomes available. Our retrieval and analysis tools are based on Java and ActiveX from Microsoft. In addition to data overlays and plots of drifter tracks, we have also built animation tools which allow viewing of large numbers of images. These tools are used as distributed objects that execute either on the server or the client. We will demonstrate these systems to Hughes and GSFC personnel in January. Full technical reports are in production and will be included in the next semi-annual report. We will continue this activity in 1997 with Hughes and MODIS funding.

With the delays in the release of the EOSDIS Core System (ECS), we have spent considerable time with the ESDIS project and the MODIS Science Data Support Team in providing input on fallback plans and basic requirements for ECS. We expect this to continue over the next several months and ESDIS works to ensure that the basic ECS is functioning in time for AM-1 launch.

Anticipated Future Actions

- Retrieve bio-optical mooring in Hawaii and analyze fluorescence data
- Refine quality assurance plan and quality flags for our data products. Specific threshold values will be defined, based on input from other MODIS products.
- Begin chemostat experiments on the relationship of fluorescence quantum yield to environmental factors. Establish relationship between fluorescence quantum yield and photosynthetic parameters.
- Hire postdoctoral level person to serve as point of contact for MOCEAN and GLI activities. Deliver V1 code to GLI oceans team and begin to define integration issues.
- Continue to develop and expand browser-based information system for in situ bio-optical data.

Problems and Solutions

Although prelaunch characterization of MODIS is still an issue, the most important issue facing us is the delivery schedule of ECS. It has become difficult to develop and test code as schedules and capabilities change.

Appendix

Manuscripts in press related to MODIS research. The first manuscript is in press in *Geophysical Research Letters*; the second manuscript is in press in SPIE Ocean Optics XIII. Figures have not been included with the first manuscript.

Chlorophyll natural fluorescence response to upwelling events in the Southern Ocean

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Abstract. Variability of solar-induced (natural) fluorescence and chlorophyll were measured on scales of hours to weeks in the upper layer of a cyclonic eddy located south of the Antarctic Polar Front using a free-floating drifter. The fluorescence signal was analyzed both in terms of chlorophyll concentration and as an indicator of energy distribution in the photosynthetic apparatus. Long-term trends in fluorescence parallel changes in chlorophyll concentration. Considering a significant positive correlation between fluorescence and the relative depth of the eddy upper layer we hypothesize that the observed short-term variations in natural fluorescence are a physiological response of phytoplankton to changes in the supply of limiting nutrients. This interpretation is consistent with the Southern Ocean iron limitation hypothesis.

Introduction

One of the major challenges in the study of carbon fluxes in global marine ecosystems is the estimation of photoautotrophic production. Large areas of the ocean are undersampled, and both spatial and temporal scales of variability are poorly resolved. Between 1979 and 1986, the Nimbus-7 Coastal Zone Color Scanner (CZCS) provided the first satellite data from which global patterns of chlorophyll in the surface of the ocean could be determined [Gordon *et al.*, 1983]. Because these maps were based on the scattering and absorption properties of pigments, they provided an avenue to estimate the amount of light harvested by phytoplankton and proved to be valuable tools in the attempt to develop empirical and mechanistic optical models of ocean primary production [Perry, 1986; Morel and Brethon, 1989]. However, only a fraction of the energy absorbed by the photosynthetic apparatus, termed the photosynthesis quantum yield (F_p), is used in photosynthesis [Butler, 1978]. The remaining absorbed energy is released in the form of fluorescence (mostly at 683 nm) and heat. The F_p varies with changes in nutrient availability, light intensity and phytoplankton species composition [Falkowski and Kolber, 1993]. For this reason estimation of the variability of F_p is required to calculate primary productivity using optical models and sea-surface chlorophyll maps.

Three new satellites, scheduled for deployment by NASA (National Aeronautics and Space Administration), NASDA (National Development Agency of Japan), and ESA (European Space Agency) between 1998 and 2000, will have the capability for measuring chlorophyll concentrations in the surface of the ocean as well as chlorophyll natural fluorescence. Apart from solar irradiance, the main source of energy measured at 683 nm in the ocean is chlorophyll [Gordon, 1979]. The variation in fluorescence quantum yield (F_p), the fraction of absorbed energy emitted as chlorophyll fluorescence during photosynthesis, is a manifestation of changes in the energy

distribution within the photosynthetic system [Krause and Weis, 1991]. Butler's tripartite model [Butler, 1978] of the photochemical apparatus predicts an inverse relationship between F_p and F_t .

Biological oceanographers have used natural fluorescence to map chlorophyll concentrations by assuming that changes in F_t are negligible [Neville and Gower, 1977], and to estimate the fraction of absorbed solar energy channeled into photosynthesis by assuming a predictable relation between F_t and F_p [Chamberlin *et al.*, 1990]. However, the inverse relation between F_t and F_p is not always straightforward. A third energy path for the de-excitation of chlorophyll is heat dissipation. Under light-saturated conditions, variations in F_t can result from changes in photoprotective pigments and heat dissipation (F_h), rather than by changes in F_p [Oliazola *et al.*, 1994]. A thorough understanding of the physiological basis of F_t fluctuations and how they relate to changes in the physical and chemical environment is a necessary pre-requisite for the accurate interpretation of remotely sensed natural fluorescence data.

Data Acquisition

Free-floating optical drifters provide an opportunity to measure variations in natural fluorescence in the surface layer of the ocean [Abbott *et al.*, 1995] and to relate these variations to changes in biological properties that can also be derived from in situ bio-optical measurements [Smith *et al.*, 1991]. Furthermore, by measuring changes within a water mass, temporal variability may be isolated from horizontal variability [Niiler *et al.*, 1987]. However, temporal variability attributed to bio-optical fluctuations observed in this manner also includes the variability resulting from the vertical movements of the water column [Abbott *et al.*, 1995].

During the 1994-1995 austral summer, and as part of the Palmer-Long Term Ecological Research program (Palmer-LTER, [Smith *et al.*, 1995]), we deployed a METOCEAN Data Systems optical drifter in the southern region of the Drake Passage (62°00'S 62°16'W, Fig 1A). The drifter was equipped with a 7-channel upwelling radiance sensor (412, 443, 490, 510, 555, 670 and 683 nm), a one channel downwelling irradiance sensor (490 nm), temperature and pressure probes. The underwater sensors and probes were located at a depth of approximately 0.3 m. A drogue, centered at 15 m depth, allowed the drifter to follow a specific water mass. Data were collected at 90 second intervals. Hourly mean and standard deviation values were transmitted via satellite (Service ARGOS) along with the geographical position of the drifter.

The concentration of chlorophyll (chl)

surrounding the drifter was estimated using the ratio between upwelling radiance at 443 and 555 nm [Clark, 1981]. Calibration parameters for this ratio were calculated based on samples collected in the study area. Shipboard measurements of upwelling radiance obtained using a Tethered SpectroRadiometer Buoy (TSRB, Satlantic Inc.), which had the same optical resolution characteristics as those of the drifter, were compared to discrete sea surface concentration of chl measured by fluorometry [Strickland and Parsons, 1972]. Chlorophyll natural fluorescence was measured at 683 nm and corrected for backscatter by subtracting the upwelling radiance at 670 nm.

Fluorescence quantum yield (F_r) is a function of the solar energy absorbed by the photosynthetic apparatus and cannot be estimated directly from the drifter data. However, because our bio-optical estimates of the chlorophyll concentration are derived from the absorption properties of phytoplankton, changes in the amount of fluorescence per unit estimated chlorophyll and per unit downwelling sea-surface irradiance at 490 nm (Ed_{490}) are proportional to changes in F_r . In our analysis we have defined an apparent fluorescence quantum yield ($F_r(Ed_{490})$) as the slope of the regression of fluorescence per unit chlorophyll versus Ed_{490} . The slope was calculated from the data collected over sampling periods averaging 48 hours (Fig. 2). For this reason the effect of diurnal photoadaptive processes in the variability of F_r cannot be extracted from $F_r(Ed_{490})$.

Variations in the vertical velocity of the water column were estimated from the conservation of potential vorticity equation [Flierl, 1979], and the drifter's measured horizontal displacement velocities. Calculations of vertical velocities using the conservation of mass equation [Pond and Pickard, 1978] provided a similar pattern of upwelling and downwelling events.

Results

Approximately one week after deployment, the drifter was trapped within a cyclonic eddy centered at approximately (60°10'S, 61°00'W). It remained in the eddy for the next 50 days describing a circular trajectory with an average radius of 19 km (Fig. 1B). During this period we observed regular short-term (days) oscillations in the fluorescence signal, $F_r(Ed_{490})$, and in the relative depth of the eddy's upper layer (h in ho^{-1} , Fig. 3) [Flierl, 1979]. Neither the temperature data, nor chlorophyll concentrations nor downwelling irradiance measured at 490 nm provide any evidence of short-term fluctuations of the magnitude and frequency necessary to explain the observed fluorescence oscillations. A long-term increasing trend observed in the natural fluorescence was also evident in the chlorophyll signal (Fig. 3).

Interpretation and Discussion

There are several potential explanations for the positive correlation between $F_r(Ed_{490})$ and h in ho^{-1} ($a < 0.001$, maximum cross correlation = 0.472 and standard error = 0.045 when $F_r(Ed_{490})$ lags 0.87 days) if we acknowledge that F_r can vary in response to changes in mixed-layer light regime, nutrient availability and the taxonomic composition of the phytoplankton population. Alterations in the mixed-layer light regime may trigger changes in the per cell concentration of photosynthetic pigments or in the ratio of accessory photosynthetic pigments to chlorophyll *a* (Prézelin, 1981). These changes could modify the absorption of radiation at 443 nm in the upper water column and affect our estimation of chlorophyll *a*. Changing the mixed-layer light regime may also induce photoinhibition and photoprotection of the photosystem [Falkowski and Kolber, 1995]. However, the lack of a strong negative correlation between Ed_{490} and $F_r(Ed_{490})$ (Fig. 3) suggests that the short-term variability observed in $F_r(Ed_{490})$ may be caused by other factors.

It is not possible with the data available to eliminate completely the possibility that the fluctuations observed in F_r are the result of changes in phytoplankton community structure. However, if we consider that the drifter is following a specific mixed-layer water mass, with a net slippage relative to the water mass of less than 1 km d^{-1} [Niiler *et al.*, 1987], then the F_r signal pattern would imply that the ecosystem sampled has two distinct communities with spatial distribution of approximately 5 km. These communities would be associated not only with different regions of the eddy but also with a different upper water layer depth (h in ho^{-1}). However, the lag period of 1 day between F_r and h in ho^{-1} and the relative constancy in the chlorophyll concentration argue against this interpretation.

We hypothesize that the observed patterns in F_r are a result of nutrient-induced changes in the distribution of energy in the photochemical apparatus. Decreases and increases in h in ho^{-1} are correlated, respectively, with positive and negative water column vertical velocities as derived from the mass balance equation. These oscillations are an indication of upwelling events. The lack of a temperature signal in these events is the result of the relatively small vertical thermal gradient in the surface waters of the Southern Ocean compared to the measurement resolution of our thermistor (0.16°C).

The Southern Ocean is considered to be a region with high inorganic nutrient concentrations and low phytoplankton biomass [El-Sayed, 1987]. Evidence suggests [Martin *et al.*, 1990] that phytoplankton productivity is iron-limited in the Drake Passage (60°46'S, 63°26'W). In this calculation it was assumed that the upwelling rate was 0.25 $m\ day^{-1}$ and therefore the iron input into the euphotic zone from these upwelling processes could sustain a phytoplankton new production rate of at most 3 $mmol\ C\ m^{-2}\ day^{-1}$ [Martin *et al.*, 1990]. Maximum upwelling rates (positive vertical velocities) derived from the drifter trajectory within the eddy range between 20-60 $m\ day^{-1}$, assuming a constant divergence in a homogeneous

surface layer 30 m deep. These rates are two orders of magnitude greater than those used by Martin et al., a result that is consistent with upwelling rates previously observed in small meanders along fronts [Pollard and Regier, 1992]. According to our observations and interpretations, nutrient stress may be significantly relaxed in the upper euphotic zone during eddy induced upwelling events. Under these conditions, a larger fraction of the energy captured by the photosynthetic apparatus could be directed towards photochemistry decreasing the amount of energy released in the form of heat and fluorescence [Kiefer and Reynolds, 1992; Behrenfeld et al., 1996]. When upwelling relaxes, the decrease in nutrient flux would reverse the trend, decreasing phytoplankton photosynthesis, and increasing the release of energy as heat and fluorescence. Because cyclonic eddies appear to be common features associated with the Polar Front in the Drake Passage [Hofmann and Whitworth III, 1985], they may represent an important, although erratic, source of iron upwelling in this region of the world ocean.

Recent field studies provided additional support to the hypothesis that iron injections stimulates phytoplankton growth rates in surface waters of the Drake Passage south of the Polar Front [Buma et al., 1991; de Baar et al., 1995] and in other pelagic environments with high nutrient and low chlorophyll concentrations [Behrenfeld et al., 1996]. Furthermore, Giedder and co-workers [Giedder et al., 1993] have shown that iron limitation strongly enhances chlorophyll fluorescence in the diatom *Phaeodactylum tricornutum* and that the physiological response to iron limitation as well as iron addition is manifested in a matter of hours. The implied short-term increase in F_p in natural assemblages resulting from iron injection has been observed during two large-scale iron enrichment experiments conducted in the eastern equatorial Pacific [van Scoy and Coale, 1994; Behrenfeld et al., 1996].

Conclusions

Considering the above observations, we hypothesize that nutrient inputs into the upper euphotic zone as a result of upwelling events may be responsible for the decreases in F_i (Ed490) detected in our field experiment (Fig. 3). If this interpretation is correct, our observation would suggest that nutrient availability is not only limiting the carrying capacity of the system but also algal photosynthesis [Falkowski et al., 1992]. Because the inherent time-scales for changes in algal biomass and physiological responses are in the order of days and hours, respectively, the study of the temporal variability of natural fluorescence in conjunction with chlorophyll concentrations may prove valuable when trying to understand nutrient limitation of phytoplankton productivity. Being able to measure the spatial and temporal variability in F_i may help to define scales of variability for the photosynthesis quantum yield.

Our results have two important consequences for the interpretation of remotely sensed chlorophyll natural fluorescence. First, when changes in chlorophyll concentrations are of the same order of magnitude as changes in the fluorescence quantum yield, natural fluorescence cannot be used to estimate chlorophyll concentration (Fig. 3). Spatial and temporal scales are critical in this analysis because variations in natural fluorescence are driven by short-term physiological responses as well as long term-changes in phytoplankton pigment biomass. Second, the variation in F_i may prove to be a useful indicator of changes in the nutritional status of phytoplankton. To date, the only remote sensing evidence for nutrient injections into the upper euphotic zone remains the increase in surface chlorophyll concentration and the decrease in sea surface temperature [Dugdale et al., 1989]. However, in ecosystems where an increase in photoautotrophic production is transferred directly to higher trophic levels, an increase in phytoplankton biomass will not occur. Furthermore, in high latitude pelagic environments where water column stratification is mainly controlled by salinity rather than temperature, upwelling events may not display a strong sea surface temperature signature. Although it is still not apparent how the absolute magnitude of the fluorescence quantum yield per se in light saturated environments can be translated into F_p , relative changes in F_i in nutrient-limited environments may provide a mechanism to monitor the relaxation of nutrient limitation as a result of deep mixing, upwelling or atmospheric dust deposition events. However, in situ experiments including the measurement of natural fluorescence, photosynthesis, and nutrient availability will be required before we can unambiguously attribute temporal changes in F_i to changes in nutrient availability.

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FIGURE CAPTIONS:

Figure 1. [A] Map displaying the trajectory of the optical drifter. [B] Detail of the trajectory associated with the cyclonic eddy.

Figure 2. Natural fluorescence per unit chlorophyll plotted versus sea-surface solar irradiance measured at 490 nm (Ed490). Regression slopes ($\Phi_i(\text{Ed490})$, see figure 3C for values) were calculated based on data collected over 48 hours intervals (open circle: January 17-18; open squares: Jan 23-24; closed squares: Jan 28-29; closed circles: Feb. 11-12; open triangles: Feb 19-20).

Figure 3. Temporal variability of [A] sea surface temperature, [B] chlorophyll concentration, [C] Ed490, [D] $\Phi_i(\text{Ed490})$, and [E] relative depth of the upper layer of the water column sampled by the drifter within the cyclonic eddy. Dotted lines in panel C show the 95% confidence interval of $\Phi_i(\text{Ed490})$.

Bio-optical drifters - Scales of variability of chlorophyll and fluorescence

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ABSTRACT

Both the California Current System and the Antarctic Polar Front are characterized by mesoscale variability and meandering jets. These meanders lead to regions of strong vertical motion, on the order of several tens of meters per day. To study physical and biological scales of variability in these two systems, near-surface drifters were released in these two environments; twenty-six in the California Current and five in the Polar Front. Each drifter was equipped with a spectroradiometer to measure upwelled radiance at the SeaWiFS wavelengths as well as at 683 nm. A temperature system was also included. Data were relayed to shore via satellite. These data were converted into biological quantities, including chlorophyll and an apparent quantum yield of fluorescence. Decorrelation time scales were calculated and compared with corresponding statistics of the physical environment. Time scales for all variables increased as the drifters moved from nearshore to offshore. The scales associated with temperature and chlorophyll were similar nearshore, but increased more rapidly offshore for temperature. This suggests that the processes regulating the distribution of temperature and chlorophyll are similar in the nearshore region and significantly differ offshore.

Keywords: California Current, upwelling, time scales, phytoplankton, drifters, chlorophyll, fluorescence

INTRODUCTION

Over the past decade, developments in smaller and less expensive instrumentation have allowed oceanographers to collect data sets at time and space scales that are difficult to observe from conventional platforms.¹ For example, time series from a fixed point mooring are a combination of both temporal changes and spatial changes as new water masses are swept past the mooring. Free-drifting buoys that can be drogued to follow upper ocean circulation help separate temporal variations in a water mass from those that occur spatially. Bio-optical drifters deployed in the California Current were initially used to examine physical and biological processes within a specific physical feature.^{2,3} The advent of lower cost sensors as well as the use of satellite data relay now allows the deployment of large numbers of drifters to conduct systematic studies of the statistical properties of the upper ocean bio-optical field. In this paper, we restrict our discussion to results of drifter studies in the California Current although some bio-optical drifters were also deployed in the Southern Ocean. Our analyses followed two paths. First, we calculated large-scale statistics of the biological and physical fields. Second, we analyzed the impact of specific physical features on upper ocean biology.

METHODS

The standard World Ocean Circulation Experiment (WOCE) surface drifters have been modified by METOCEAN Data Systems to include a Satlantic spectroradiometer (OCR-100) in the bottom of the surface float. This sensor measures upwelled radiance at 412, 443, 490, 510, 555, 670, and 683 nm. The surface float also includes pressure and temperature sensors. A Satlantic narrow band irradiance sensor (ED-100), centered at 490 nm, is mounted in the top of the surface float. A 40 m long drogue is attached below the surface float such that the drifter responds primarily to currents at 15 m depth. Data are averaged over 60 minutes and then transmitted. If a NOAA polar-orbiting satellite is in range, then the message is relayed to shore. Otherwise the message is updated the next hour and the new message transmitted. On average, approximately eight messages were received per day in the California Current and fifteen in the Southern Ocean. The data set also includes "housekeeping" information from the drifter such as battery voltage, number of samples, average time that the surface float was submerged, etc.

Twenty-six drifters were released over a three-year period in the California Current. Three drifters failed soon after deployment (presumably due to high seas); the remainder had an average lifetime of six months with the maximum being nearly ten months. Figure 1 shows all of the drifter tracks collected between 1993 and 1995. Most of the drifters were deployed along a line at 39.5°N between 125° and 128°W. As expected, the general trend is for the drifters to move south and west with the prevailing summertime currents (when most of the drifters were deployed). To date, only five drifters have been released in the Southern Ocean: two in Drake Passage and three in the Polar Front at 170°W. These last three drifters are equipped with a Global Positioning System (GPS) transmitter to provide more accurate location information.

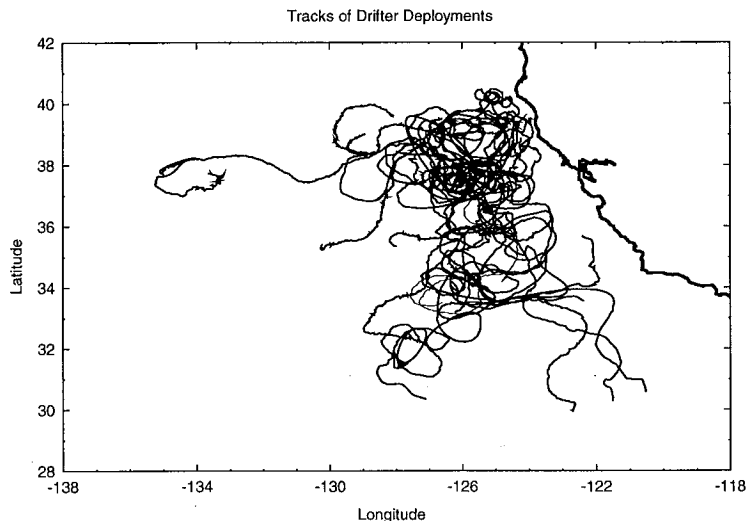


Figure 1. Composite view of drifter deployments in the California Current System in 1993-1994.

Once the data are received, several screening tests are applied to eliminate low quality data points. Occasionally bits are dropped from the Service Argos transmissions, resulting in unrealistic values in many of the drifter variables such as battery voltage, downwelling irradiance, etc. Argos data files also include the position of the drifter. Sometimes these positions are either missing or are obviously in error (sudden, large jumps in position, etc.) The Argos files also include the number of messages received during a given transmission from the drifter. If this number is small, then the probability of erroneous or corrupted data increases. We also screen for bio-fouling (through examination of the level and variability of the 683/555 radiance ratio) and test faulty bio-optical measurements through examination of band ratios. However, the largest amounts of data removed through screening occur when we eliminate those records that were obtained when the absolute solar angle (elevation) is less than 20°. This constrains the study data set to observations collected with a few hours of local solar noon.

After screening, chlorophyll is calculated using the following equation:

$$chl = 0.56353 * \left(\frac{L_u 443}{L_u 555} \right)^{-0.595} \quad (1)$$

where L_u is upwelling radiance at a specific wavelength. This form is derived from earlier bio-optical models,⁴ and the coefficients are based on comparisons with chlorophyll samples collected near one of the drifters in 1994.

Once the data files were cleaned and the various derived quantities were calculated, we then estimated decorrelation scales from the drifter data set. We calculated a “daily average” for the variables of interest: SST, chlorophyll, fluorescence/chlorophyll, and drifter speed. Some of the data records were too short or too gappy for further statistical analyses. However, the majority of the drifters were nearly complete with only occasional missing data

points. These gaps were filled using linear interpolation between adjacent days. A linear trend was removed from each time series, and the autocorrelation function was calculated. The decorrelation scale was estimated as the point at which this function first became insignificantly different from zero. Figure 2 shows a typical pair of autocorrelation functions for SST and chlorophyll from one drifter in the California Current. Cross-correlation functions were calculated in a similar manner between detrended time series of SST and chlorophyll.

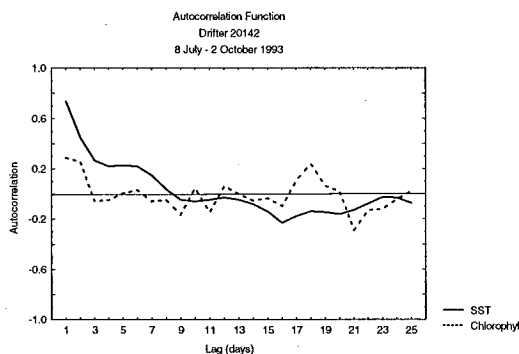


Figure 2. Autocorrelation functions of SST and chlorophyll from drifter 20142. The decorrelation scale is approximately 6.5 days for SST and 2.5 days for chlorophyll.

RESULTS AND DISCUSSION

The average length of the bio-optical time series was 73 days before fouling became evident, although some drifters lasted well over 90 days before there was any evidence in the bio-optical signals that fouling had occurred. For these long time series, it was possible to divide the record into two parts, each one covering a different season. As part of our analysis, we also calculated the average distance from the coast for each drifter.

The average decorrelation time scale was longest for SST at 6.3 days. The decorrelation scale for chlorophyll was 3.7 days, 2.3 days for fluorescence/chlorophyll, and 3.3 days for drifter speed. These results are within the range for the same region off northern California from a study using time series of satellite imagery of chlorophyll and SST.⁵ In that study, it was found that the time scales were between one and seven days, depending on length scale.

Figure 3 shows the decorrelation scale for SST, chlorophyll, fluorescence/chlorophyll, and drifter speed as a function of average offshore distance of the drifter. We have divided the distance offshore into three categories: <200 km (nearshore), >200 km but less than 400 km (transition), and > 400km (offshore). There is a general trend for SST and chlorophyll scales to increase as one moves offshore, but this is by no means consistent. However, the more interesting result is that the time scales associated with SST and chlorophyll are relatively similar in the nearshore and diverge as one moves offshore. This suggests that the processes governing SST and chlorophyll are similar in the nearshore region whereas they are controlled by different processes offshore. This is in contrast to earlier results⁵ where no significant differences could be detected between the SST and chlorophyll fields. Coastal upwelling should control both SST and chlorophyll in the nearshore, whereas different physical processes or perhaps changes in the biological community lead to different statistical properties of the fields offshore. Another feature of Fig. 3 is that fluorescence/chlorophyll shows more variability nearshore (shorter time scales) whereas it is nearly equal to the chlorophyll time scale offshore. Rapid changes in fluorescence relative to chlorophyll concentration are indicative of variability in the distribution of energy in the photochemical apparatus of the phytoplankton. This observation suggests that in the nearshore region, the time scales of physiological adaptation are significantly shorter than the time scales of changes in phytoplankton biomass.

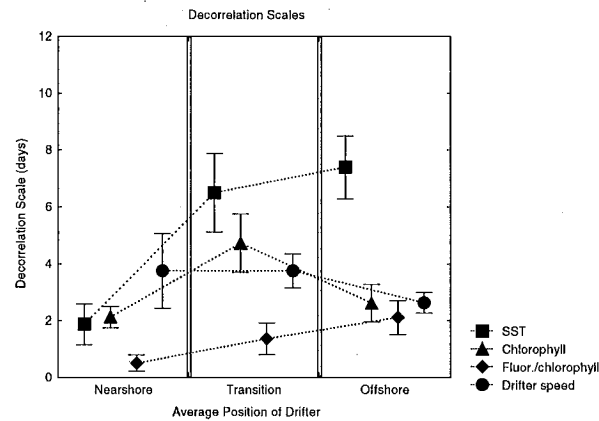


Figure 3. Average decorrelation scales for SST, chlorophyll, fluorescence per unit chlorophyll, and drifter speed as a function of distance offshore. The boxes represent ± 1 standard deviation and the whiskers represent ± 1 standard error.

Figure 4 shows the track and cross-correlation function for drifter 22622. The drifter made nearly two complete circuits around a large anticyclonic eddy. Note that changes in SST led changes in chlorophyll by one day. Figure 5 shows the same information for drifter 20139 which made two circuits around a much smaller, cyclonic eddy. Although it is not possible to draw robust conclusions from results from two eddies, it is worth noting that the negative correlation (at near zero lag) is much larger in the anticyclonic eddy than in the cyclonic eddy, whereas the cyclonic eddy has large, negative lobes at ± 12 days. The time scale of the positive correlations (twelve days for 22622 and six days for 20139) corresponds to the travel time around the eddy (cold water, high chlorophyll on the south side of the eddy and warm water, low chlorophyll on the north). Earlier evidence of a lag between SST and chlorophyll was found in only one region off northern California.⁵ It was inferred that this region was near an upwelling center, and that the lag was the result of the delay in biological processes responding to high nutrients in the surface water. In comparison, many of the drifter deployments revealed that changes in SST led changes in chlorophyll by roughly 1-2 days. However, most of the drifters were released in active upwelling regions, and we suspect that the satellite imagery⁵ was simply not adequate to evaluate these small time scale patterns.

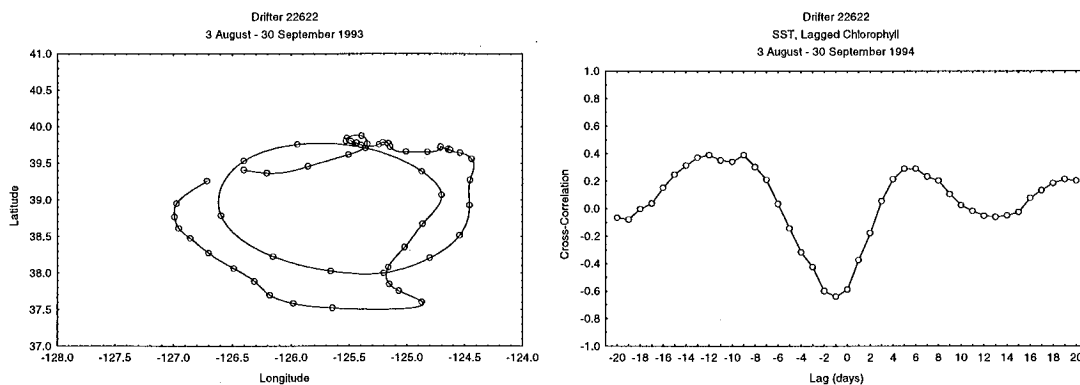


Figure 4. (Left) Track of drifter 22622. (Right) Cross-correlation function of SST and chlorophyll. Negative lags indicate that SST leads chlorophyll.

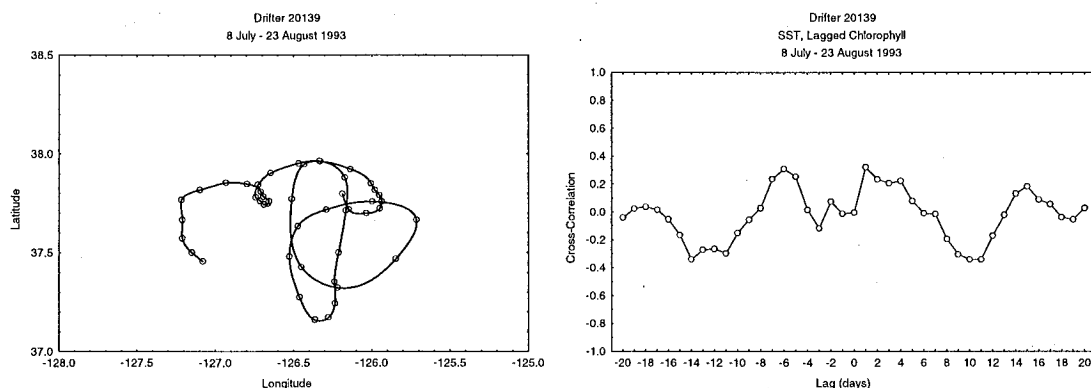


Figure 5. (Left) Track of drifter 20139. (Right) Cross-correlation function for SST and chlorophyll.

Although the optical sensors are calibrated by Satlantic, there are few opportunities to compare readings between sensors in the field unless two or more drifters are found simultaneously sampling the same water mass. Drifter 20140 (not shown) also traversed the same eddy as 22622 (Fig. 4) several days later. Drifters 20140 and 22622 were deployed at 39°33'N, 124°55'W and 39°25', 126°27'W respectively. Although these drifters were released approximately 130 km apart, they followed the same circulation path over a period of 50 days with an average lag time of 18 hours and average distance of 62 km between drifters (Fig. 6, top).

When comparing the temperature records between sensors mounted in these two drifters we observe that both instrument packages appear to be sampling different water masses over the first 30 days (Fig. 6, middle). However, following day 245, the temperature records display strong similarities in the magnitude and trend of the readings, suggesting that both drifters are located in the same water mass. It is also during this period that the distance between both drifters is reduced to an average of 18 km (Fig. 6, top). Furthermore, estimates of algal pigment concentration (chlorophyll a + phaeopigments) also display strong similarities during this period. This observation suggests that, at least in this particular case, the principal physical and biological processes controlling phytoplankton biomass over temporal scales of days appear to be acting over large spatial scales (1-100 km).

Similar trends over the same time period are observed when normalizing the upwelling irradiance at 683 nm (L_u683) and 670 nm (L_u670) to the downwelling radiance measured at 490 nm (E_d490). However, because the absolute value of these measurements differs by a factor of 1.7 between drifters, it is not possible to convert our records into absolute fluorescence quantum efficiency of chlorophyll a. Nevertheless, it is still possible to compare the variance in algal pigment concentration to the variance in relative chlorophyll natural fluorescence. Multiple regression analyses, using model II geometric linear regressions, suggests that the variance in chlorophyll fluorescence is correlated with changes in chlorophyll concentration. However, the correlation coefficient of the regression low ($r=0.45$, $p < 0.05$) suggesting that the variance in chlorophyll concentration and E_d490 contribute only partially to the variability in absolute chlorophyll natural fluorescence in these water masses.

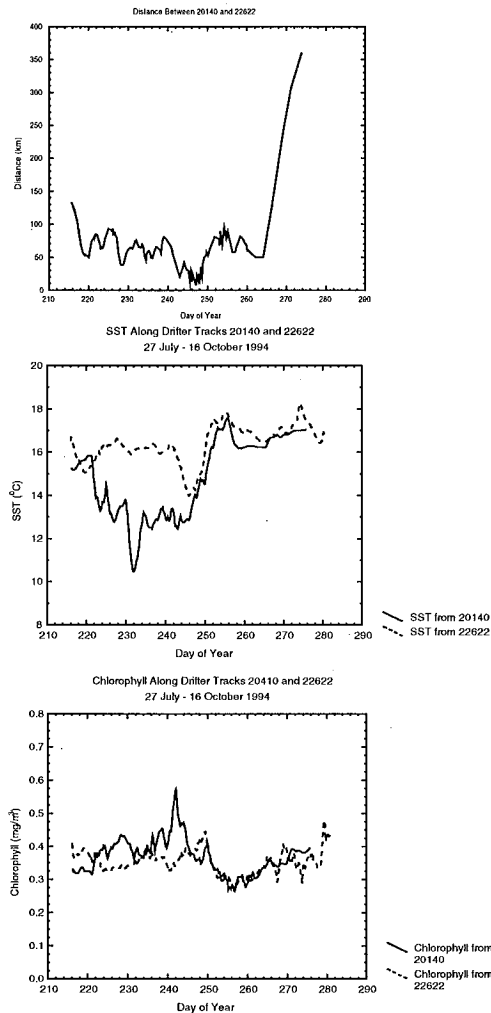


Figure 6. (Top) Distance between drifters 20140 and 22622. (Middle) SST from drifters 20140 and 22622. (Bottom) Same except for chlorophyll.

CONCLUSIONS

Time scales of SST, chlorophyll, and fluorescence/chlorophyll increase as one moves offshore. This is to be expected, given the higher levels of mesoscale variability near the coast.⁵ Complex interactions of local wind forcing and ocean circulation should result in intense heterogeneity of vertical motions in the upper ocean, thus affecting SST and nutrient availability, which in turn will affect phytoplankton abundance. This leads to a separation in the statistics of the two data sets, with SST having in general longer time scales than chlorophyll. Although coastal upwelling and presumably rapidly growing phytoplankton dominate the nearshore environment,⁶ both biological and physical processes in the offshore environment may be quite different. Historical evidence suggests that the offshore phytoplankton community is dominated by small, slow-growing forms⁶ which may lead to a decoupling between the physical processes governing SST and those governing chlorophyll. Given the time scales of phytoplankton growth, we expect to see a lag between changes in the physical environment and the biological response. As most of the drifters covered the summer season, we cannot determine if there is any seasonal modulation in these patterns. Of note is that the decorrelation scales are relatively small, implying that these mesoscale processes will continue to be difficult to resolve with conventional ship sampling.

These interpretations can be further complicated by temporal and spatial changes in the bio-optical models themselves.³ That is, changes in fluorescence efficiency, particulate backscattering, chlorophyll package effect, etc., will be manifested as changes in chlorophyll abundance and other derived properties. We expect that such changes will act to decrease the decorrelation scales, so that the estimates provided here are likely to be an upper bound on these scales.

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